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The blast furnace trazability by helium

Rafael Barea[^], Ramón Martín D*, I. Ruiz Bustinza*
and Javier Mochón*

[^] *Nebrija Universidad, Pirineos, 55, 28040 Madrid Spain*

* *Centro Nacional de Investigaciones Metalúrgicas (CENIM of CSIC)
Avda. Gregorio del Amo, 8, 28040-Madrid. Spain*

1. Introduction

Blast furnaces (BF) may be considered to be among the oldest type of industrial equipment that is still used regularly today. Blast furnaces existed in China from about the 5th century BC, and in the West from the High Middle Ages. They spread from the region around Namur in Wallonia (Belgium) in the late 15th century, being introduced to England in 1491. With a few variations, they have been used for over 600 years.

The steel industry uses blast furnaces to chemically reduce iron ore (mainly oxides), removing oxygen and enriching the ore into metallic iron with a high degree of metallization (total iron content higher than 95-96%), from which is obtained pig iron (Aranguren, & Mallol, 1962) which is the raw material used in the integrated steel industry to manufacture steel (UNESID, 1998).

A blast furnace is a vertical reactor comprising an assembly of cylindrical or conical elements (Figure 1). Among its most important features are the internal volume, which is determined by the diameter of the crucible, the furnace bottom, defined by the desired results, which collects both molten metal and slag. Thus a furnace crucible which is 12 meters in diameter can produce more than three million tons of pig iron annually.

The blast furnace is a countercurrent reactor in which the reducing gas is produced by coke gasification with the oxygen blowing via tuyeres. The reducing gas flows upwards reducing the iron ores charged at the top of the furnace. The blast furnace process is very complex with many influencing and correlating factors (Steiler, 1998; Kundrat, 1989).

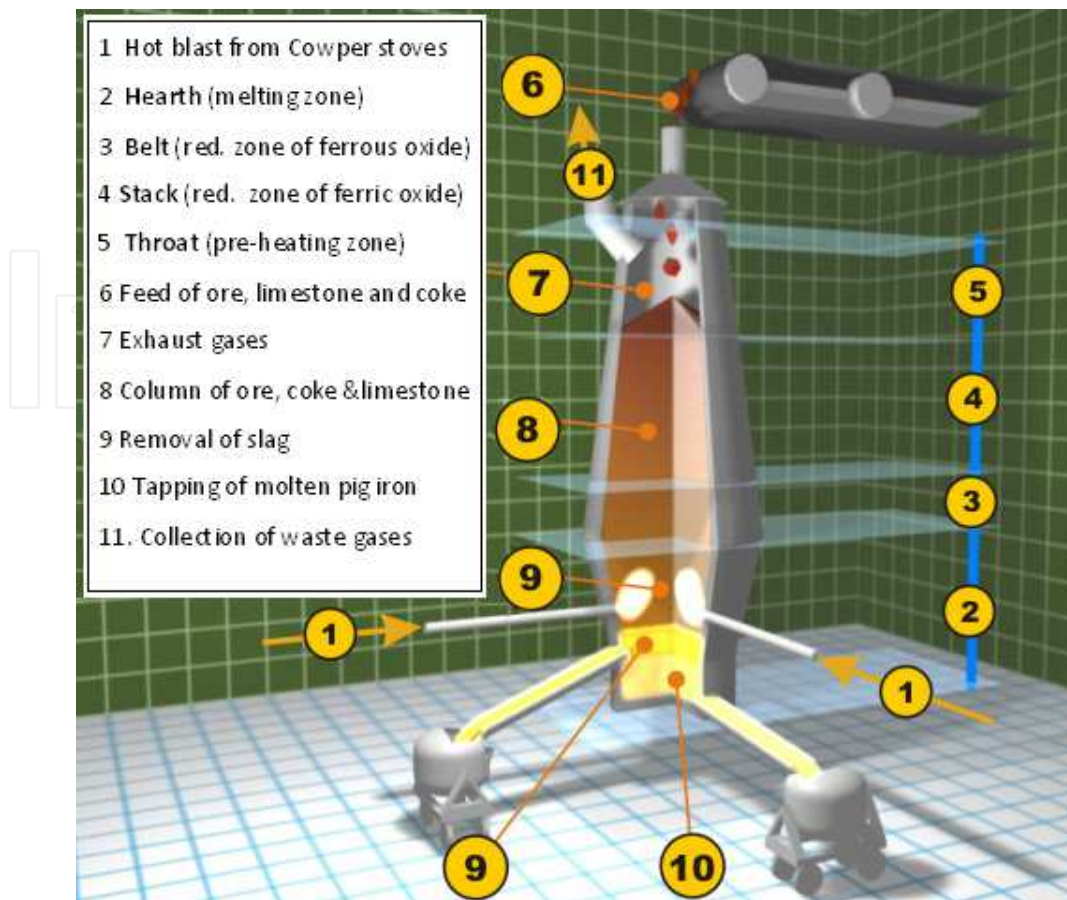


Fig. 1. A Blast furnace diagram:(1) Hot blast from Cowper Stones (2). Hearth (melting zone). (3). Belt (reduction zone of ferrous oxide) (4). Stack (reduction zone of ferric oxide) (5). Throat (pre-heating zone) (6). Feed of ore, limestone and coke (7). Exhaust gases (8) Column of ore, coke and limestone (9). Removal of slag (10). Tapping of molten pig iron (11). Collection of waste gases

2. The Blast Furnace

2.1. The main parts of blast furnaces

The primary systems and most important components are:

- (a) Gas Evacuation System: Consists of drainage pipes for the gas produced and comes equipped with relief valves and controls for pressure, temperature, gas composition, etc. (items 7 and 11 of the Figure 1).
- (b) Oven Body: The oven itself, built with refractory materials with different characteristics, depending on the needs of each area and the furnace construction. Its design provides for the operations required, and the chemical exchange between solids and gases, which coexist in various proportions in each area. The design of the kiln is variable, along with its height, distinguishing different areas, which are described later.
- (c) Cooling System: Varies according to each zone in order to provide the most intense, efficient performance to maximize system reliability, refractory lining durability, and, consequently, optimize the duration of the furnace campaign. It normally requires several closed cooling circuits, in addition to control systems for

temperature, pressure, flow, heat loss calculations, detection of leaks or failures of refrigerated units, etc.

- (d) Control System: To manage the operation of the furnace equipment, this system is made up of a large number of sensors (temperature controls, pressure, level sensors, gas analysis sensors, etc.) which, together with its ancillary facilities, form a global control system.

Inside the blast furnace there are different chemical zones:

- (a) Throat (see Figure 2 and Item 5 in the Figure 1): The top of the oven where raw materials such as iron ore, coke and flux are charged. Formed by straight walls, loading should ensure a controlled distribution of each material inside the oven. Currently the most common system for controlling load distribution, designed by Paul Wurth, is a system using a gear box, allowing pellets to be downloaded inside the oven in a homogeneous way.
- (b) Stack: (see Figure 2 and Item 4 in the Figure 1) located between the end of the hopper and the belly of the furnace, it contains most of the load and has a truncated cone shape. This part of the blast furnace has the job of encouraging the exchange of heat between solids and gases.
- (c) Belt : (see Figure 2 and Item 3 in the Figure 1) This is the wider part of the furnace, and it's cylindrical in shape with straight walls. As the charge descends and the temperature ascends, more space is needed as volume increases. This area of the kiln is the link between the stack and the hearth.
- (d) Hearth : (see Figure 2 and Item 2 in the Figure 1): This is the furnace area where air is injected into the hot blast from the stoves. The warm air reaches a circular tube that is inserted into the furnace through holes in nozzles. Its mission is to enable the combustion of coal. Auxiliary fuels are also injected through nozzles. The number of nozzles, which are always located equidistantly around the furnace, varies from one oven to another depending on the oven size.
- (e) Crucible: (see Figure 2) This cylindrical shaped part is the bottom of the furnace, where the products obtained in the process, pig iron and slag, are collected through a trough. The crucible is the most critical part of the plan for the selection and installation of refractories. The material used is carbon (2 m thick in the walls and 2-3 m for the bottom). In all other areas of the BF, the refractories are generally of an aluminous type and, in some specific areas, more durable materials (SiC or Sial) are used.

2.2. Blast furnace control

Control of the blast furnace process requires significant measures to ensure adequate progress and manufacturing facilities related to the making and sintering of coke. This is to maintain a stable oven operation and to control and protect the functioning of the equipment installed. With this in mind, sensors and measuring equipment are used to control the movement of materials and fluids in and out of the oven.

Specific controls include:

- (a) Input: raw materials, main and auxiliary fuels, hot blast, oxygen injected into the blast, steam injected with the hot blast (control of humidity, etc.).

- (b) Inside the furnace itself: Screening and loading of raw materials, hopper and system of distributing charge, pressures and temperatures in different parts of the oven, charge levels, charge samples in different areas, etc.
- (c) Output: iron and slag, gases, dust and sludge recovered, and so on. Of particular importance are controls for the distribution of the hopper charge and the metallurgical variables that define the process, drawing on metallurgical models of balancing heat and matter, in addition to statistical quality control, artificial intelligence, etc..

All of these factors combine to achieve stable operation of the BF in order to increase productivity, improve product quality (pig iron, slag), increase the duration of blast furnace functionality and reduce costs (minimum consumption of coke and auxiliary fuel, etc.).

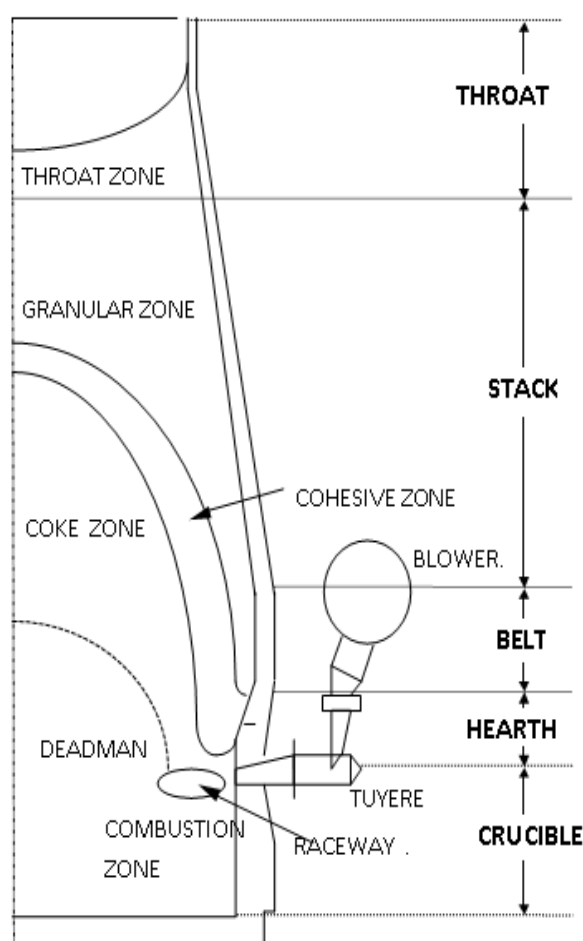


Fig. 2. The main parts of blast furnaces

One of the key aspects that influence productivity (t/m^3 useful volume / day), production (t / year) and duration of a blast furnace campaign, measured in total output in relation to the size of the oven, is optimal control of the process that results in steady oven production.

Other aspects that influence production, productivity, and campaign duration are:

- The BF design (profile, crucible diameter, etc.)
- The strategy chosen to obtain a particular product (iron quality, etc.)
- Coke quality and the use of auxiliary fuels such as coal
- The ancillary equipment which facilitates peak charge distribution (hopper), high temperature blower (blast), optimal oxygen injection, work counter, level and regularity of the furnace functionality, and so on
- The original design quality of the equipment, such as the binomial refractory / cooling, equipment reliability, applied technologies, etc.
- The quality of operation and maintenance processes
- The quality and type of raw materials used (percentages and types of sinter, pellets, etc.).

2.3. Blast furnace functions

The functions to be performed by a BF are quite complex, if the process is to result in the required production volume in an economical fashion. These functions include a number of mechanical operations, since the furnace needs to constantly and steadily bring the charge of solid materials (coke, ore and flux) being placed in the hopper in rapid and evenly distributed contact with the ascending gas stream.

For this to happen on a regular basis, the charge must be highly porous and very well distributed so that its interaction with the hot gas flow is homogeneous. The greater or lesser porosity of the charge depends on the shape and dimensions of the pieces being used, with greater porosity being associated with spheres of equal size, tangent and centers at the vertices of a cube. In this case, the empty spaces left between the spheres represent 52.3% of volume. If the spheres were of equal tangent, but with centers at the vertices of a rhomboid, the empty spaces would be 47.7% at most.

In practice, the pieces of ore are not spherical and do not have the same dimensions, so fine pieces caught in larger pieces can significantly lower the porosity of the load. It can be seen, therefore, that preparing and classifying the charge is important, sintering the fine pieces while leaving the larger relatively homogenous ones untreated, as is the trend in BF operations. The type of hopper, Wurth or with bells, and the loading pattern are also essential for optimal distribution.

In the case of using a hopper with bells, IHI or MOHR, the inclination of the closing bell, the relative diameter of the bell and the hopper and the length of the bell, all influence the form of distribution of solid materials in the oven hopper. The specific weight of the materials in the charge and its angle of repose are also relevant.

In addition, the BF must distribute the load so as to permit a regular descent without forming particular passageways, which would give rise to problems. Nor should the charge preferentially descend by the furnace walls or through the center of the hot gases, which means that the distribution of both fine and larger pieces must be carefully controlled throughout the area of descent.

Besides all this, as the descending charge undergoes changes in composition, temperature and volume, the design of the BF must promote these changes and the rapid, steady and consistent descent of the charge, slag and iron formation and casting at the bottom, as well as the release of gases at the top.

2.4. The deadman

The part of the furnace called the deadman, between the belt and the crucible, greatly impacts the entire process. It plays a key role in hot metal quality. The condition of the deadman has a strong influence on hot metal temperature and composition, and flow conditions. When hot metal can flow freely towards the tap hole and the deadman is a porous coke bed, then conditions are good for the desulphurization and carbonization of hot metal. The deadman also has a significant effect on lining wear and campaign length as it controls hot metal flow in the hearth.

2.5 Improving the Productivity

The blast furnace productivity is the quotient between possible gas throughput per unit of time and required specific gas generation for one tonne of hot metal obtained (Harting et al., 2000). Consequently, a productivity increase requires an increase in the gas throughput, which implies, on the one hand, improvement in furnace permeability and, on the other hand, a reduction in the specific gas requirements so then finally means a reduction in the specific consumption of reducing agents. Permeability is a measure of the gas ability to pass through the bed of solid materials; if the permeability in the furnace is higher then the furnace burden movement and the reducing gas flow through the furnace are better (Pandey et al., 1996).

The search for improvement of overall blast furnace permeability results thus in further improvements in the following fields:

- burden composition and quality,
- behaviour of burden during reduction,
- the cohesive zone shape and position control
- liquid evacuation from the hearth (slag quantity, coke size and liquid flow conditions in the hearth and tapping practices).

In all these fields, the actions aiming at permeability improvements are generally beneficial for the consumption of reducing agents, making it possible to decrease the specific gas consumption, and thus to obtain high productivity easier. Beyond that, the oxygen enrichment of the blast is the major way to decrease the specific gas volume. However, this thing will only be applicable in combination with tuyere injection in order to maintain a sufficient gas quantity to overheat the burden (top gas temperature higher than 100°C); in addition, the oxygen enrichment of the blast will be adjusted to maintain the RAFT (Raceway Adiabatic Flame Temperature) in a sufficiently high value to ensure a good gasification of the reducing agent injected, but not too high to avoid mechanical problems on tuyeres (Formoso et al. 1999). The objective "high levels of injection of pulverized coal" (and thus low coke consumption) is not only compatible with productivity, but also even necessary to increase the blast furnaces productivity (Babich et al. 1996) (Babich et al. 1999).

Permeability of the ferrous burden and coke column for the gas flow is linked together with the increases of gas throughput. A burden column (structure of charged materials, ores and coke, with properties that extensively assure the necessary void for an adequate permeability, in spite of mechanical, thermal and melting area) are down to the lower furnace. The main function of coke is guaranteeing the permeability for the gas in the dry

region above the cohesive area, in the cohesive area itself and in the hearth. In the cohesive zone the coke has an important role because the softening and melting iron-bearing materials can form an impermeable layer (Busby et al.1994)(Sert et al, 2004). Therefore, many quality criteria for ferrous burden materials and coke have been defined with ever increasing demands. In all cases, the general practice has shown that it is advisable to prepare an homogeneous mix of all iron bearing components before charging to the blast furnace, to achieve excellent permeability and suitable melting behaviour.

Then the gas distribution control is the results of a compromise among different requirements (Steiler, 1998):

To achieve a control gas flow in order to maintain the shaft permeability in spite of higher levels of injection of pulverized coal. .

To adjust the gas flow along the wall between two limits, in order to guarantee low heat losses and the absence of scaffold simultaneously

To achieve efficient gas solid flow in order to promote efficient reducing conditions and low reductant rate.

The blast furnace optimization implies that the process monitoring has reached a high standard to control the process in its inner part. Special importance has the optimisation and control of composition and gas distribution and the pressure losses inside the furnace.

Several indirect measurements (thermal losses, gas analysis and temperature recorded by burden probes) help to capture information over the gas distribution in the blast furnace (Nikus & Saxen, 1996)(Nicole et a. 2000). With the objective to develop new tools to improve the gas distribution monitoring the helium tracing techniques has been tested (Havelange, 2000). This method is employed to monitor the gas transfer time from tuyere to the burden probe. The analysis of this transfer time from the tuyere to the top and its relationship with the process would be explained.

3. Experimental method

3.1. Theory

Helium tracing technique consists in to inject helium in the blast furnace at the tuyeres level and its arrival at the blast furnace top is detected by a mass spectrometer. The spectrometer indicates the helium content in outboard gas and it is possible to define the transfer time as the delay between the injection moment and the time when helium concentration reaches 10 percent of the maximum detected level.

Inside the furnace the gas composition has an evolution from the tuyeres (where the gas is mainly composed for O_2 and N_2) to rotating chute (where the gas is mainly composed for CO_2 , CO , H_2 and N_2). The initial oxygen, the oxygen produced in the decompositions of oxides and water, participates in the production of CO , CO_2 and H_2O . The detected He ppm would be lower when more mass of gases (CO_2 , H_2 and CO) is produced. Using this data, it's possible to obtain an indirect measure of the oxidant reactions that has been produced inside the furnace. The air is more weightable after oxidant reaction then the measured of He ppm is lower. As gas composition introduced in tuyeres is similar and the He content is

the same, the maximum He ppm content measured in top of the furnace can be related with the reactivity inside the furnace.

In this work the charge in the blast furnace will be treated like ceramic foams. In all cases perpendicular section to the flow and the average velocity may be based on the entire cross sectional area.

Using the Blake-Kozeny equation or Kozeny-Carman equation, when there is a laminar flow in a porous medium, and the Burke-Plummer equation, when the flow is turbulent, then the generalised Ergun's equation (Ergun, 1957) is obtained for all-laminar to all turbulent flow.

$$\nabla P = - \left(\frac{150(1-\phi)^2 \eta}{\psi^2 D_p^2 \phi^3} + \frac{1,75(1-\phi) \rho}{\psi D_p \phi^3} |\vec{u}| \right) \cdot \vec{u} \quad (1)$$

where,

P = pressure (Pa)

u = vector of velocity (m/s)

ψ = shape factor (-)

η = viscosity of the fluid (Pa s)

ρ = fluid density (Kg/m³)

Φ = porosity (-)

D_p = particle diameter of the granular medium (m)

In other way Darcy's law (Gisonni 2003)(Hager 1994) was based on experiments with the pressure drop Δp measured over a finite length, L, in a sand pack of permeability tensor, k, and cross-sectional area, A. For linear flow of an incompressible fluid of viscosity η through this sand pack, the flow rate is related to other factor.

$$\vec{u} = - \frac{\vec{k} \cdot \nabla P}{\eta} \quad (2)$$

The Darcy's equation has been used to establish a relationship between the fluid speed and the permeability as function of the difference of pressures and gas viscosity. The gas speed is obtained dividing the distance travelled by the transfer time. Making the assumption that the instant permeability is constant in the furnace (an averaged permeability) then the permeability tensor is simplified to a constant. In this work the distance travelled by the gases and the gas permeability will be supposed constants for all the measures. The distance travelled by the gases and the permeability of the furnace k, can be calculated from the equation (3)

$$k = \frac{C}{t \cdot \nabla P} \tag{3}$$

Where C is a constant and t is the transfer time. It is possible to obtain transfer times in six points using the in-burden probe, so it is possible to establish a mean permeability burden distribution from the tuyeres up to the burden probe.

The sampling of gas for its analysis through the in-burden probe what allows comparing directly the results of the helium tracing technique with the gas composition and temperature obtained by means of the probe.

For the burden probe configuration, the journey carried out by the gas from the injection until the detector, does not vary with the measurement point, because the probe is a burden tube in whose end is the detector and filter. Its flow rate is measured to detect clogging of the sampling line. The helium concentration is measured by a mass spectrometer.

To clean the pipes before the injection of helium, a three ways electrovalve is attached to the system to let the injection of N_2 . This will ensure not only the cleaning of the pipes but also will avoid any false measurement of helium concentration and time transfer due to the presence of residual helium in the pipes.

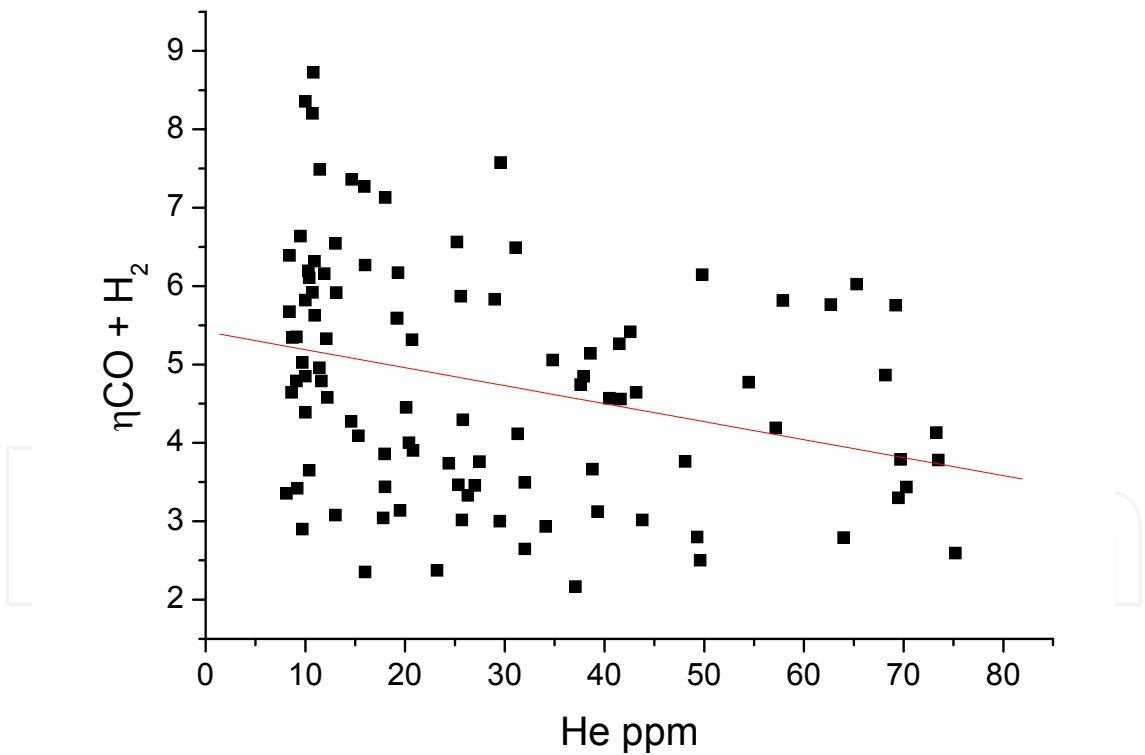


Fig. 3. It can see that higher maximum He ppm are detected, lower gases area reacting inner the furnace

2.2. Measurements

The probe measures in 6 points along a radius of the furnace from nearest area to the wall up to 4, 96 meters of the wall, near the furnace centre. When the temperature in the centre is very high (hotter than 950 °C) the probe is not introduced until the last point, and in those cases the last measures are lost.

t1 (s)	t2 (s)	t3 (s)	t4 (s)	t5 (s)	t6 (s)	Max1 (ppm)	Max2 (ppm)	Max3 (ppm)	Max4 (ppm)	Max5 (ppm)	Max6 (ppm)
99.3	204.7	260.7	417.9	338.9	517.5	18.0	17.9	10.8	14.6	11.4	10.7
31.3	167.7	334.2	388.9	364.7		32	25.4	15.3	12.2	10.9	
29.2	103.9	108.7	117.5	198.0	433.5	34.1	11.6	10	8.7	8.4	8.2
28.2	102.6	159.6	189.0	298.3	368.9	37.1	9.7	11.4	9.1	10.7	8
62.2	121.2	135.0	260.9	342.1	486.7	32	37.6	13.1	10.4	10.9	13
20.5	122.3	179.2	258.0	397.2		48.1	19.2	41.5	25.2	19.2	
123.0	181.7	299.3	288.8	303.2	337.2	31.3	37.9	62.7	42.6	31.1	34.3
99.0	117.7	123.9	186.4	283.2		25.7	73.3	43.2	25.6	10.3	
153.3	205.3	323.6	356.8	536.5		70.3	20.1	9.1	8.4	11.9	
136.3	217.8	300.4	328.0	478.7		64	27	9.7	15.9	29.6	
240.8	249.1	247.0	182.1	454.5		75.2	69.5	20.7	57.9	65.3	
84.4	99.2	147.8	275.5	144.5	517.1	23.2	19.5	8.1	27.4	54.5	17.5
176.4	268.2	262.7	438.2	212.8		16	10.4	25.8	20.4	34.8	
39.0	248.7	379.7	406.7	397.1		39.3	43.8	14.6	10.7	10.8	
119.6	116.8	181.1	259.3	478.8		17.8	41.6	19.3	18	10	
112.6	128.5	127.4	194.9	317.0		49.6	26.3	57.2	69.2	16	
135.6	233.2	369.9	433.8	496.1		29.5	73.5	10	29	13	
116.0	226.1	281.9	342.6	435.8	448.9	24.4	69.7	20.8	40.5	68.2	51.1
45.1	288.2	284.5	297.2	312.1	308.0	38.8	9.2	10	38.6	49.8	17.1
96.1	145.3	217.2	373.9	435.5	548.5	49.3	13	8.6	12.1	9.5	8.6

Table 1. Results of the measurements realised with He tracing technique. On the left of the table it can be observed the normalised transfer time in all points of measure from wall (point 1) up to centre of furnace (point 6). On the right side of the table we can read the He concentration at the top or furnace. When the furnace was hotter the last point (in the centre) did not measure.

It is necessary to correct the total transfer time previously obtained (ti) because the gases are picked up to different temperatures. When a furnace area is higher temperature, the gases go up quicker and the transfer time is reduced, but that does not indicate that the furnace has a better real permeability. As the hottest furnace is the central area if the influence of temperature is not corrected, seems as if a bigger permeability in the central area and a smaller flown in the wall exist. Then, it will be used a normalised transfer time (tn) (equation)

that will be independent of the temperature (T_b) inside the blast furnace. " t_n " enables more reliable comparisons than " t_i " when the gas flows faster because the gas temperature is higher although the permeability inside the furnace is not better.

$$t_n = \frac{T_b}{T_N} t_i \quad (4)$$

The helium concentration was measured by a spectrometer and its maximum was employed to predict the gases concentration in the furnace. Its concentration is a ratio between helium mass and air mass and although helium mass is constant, because is an inert gas, the air mass change with the reactions produced in the furnace.

$$ppm_{He_measured} = \frac{m_{He}}{m_{Air}} \quad (5)$$

3. Discussion

The quantities of CO and CO₂ at the top gas are related to each other in the parameter etaCO

($\zeta CO = \frac{CO_2}{CO + CO_2}$) calculated in each point of measure; however the lineal correlation

among maximum He ppm in each point and measured etaCO is always negative and small (lower than 0.2) what would indicate that it is necessary to consider more influence factors.

The detected fraction of H₂ in the top of furnace is higher than in the air due to the inner reaction in furnace. Consequently, the compounds form heavier gases; therefore, to more H₂ less He ppm should be detected. Whether etaCO and H₂ are added, a negative correlation with detected He ppm of the 0.3 is obtained (see Fig. 3). It is possible that it exist other variables that influence in this relation but we did not study in this paper. Therefore, higher maximum He ppm are detected, lower gases are reacting inner the furnace.

On the other hand, helium employs more time ascending when the burden is less permeable so that there is more time for the inner reactions takes place. It is possible to have an indicator about how the reaction in the burden evolves if it is computed the ratio between both variables (time in seconds/maximum He ppm). This ratio will name "Reaction" and when the time increases or the ppm diminishes, this parameter (Reaction) increases indicating that bigger reaction takes place in that area. The average measure of this variable in each point is show in Fig. 4:

The outliers can be used to detect anomalous situation. For this reason all measures evaluated as "normal state" were selected to calculate the mean value of the variable Reaction.

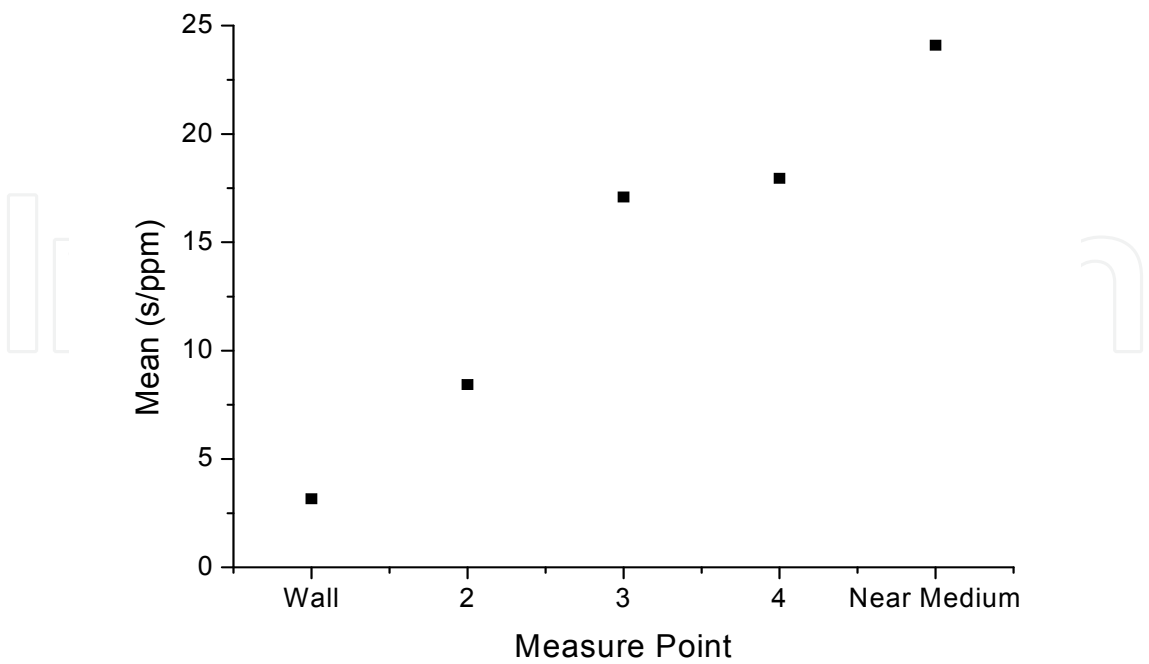


Fig. 4. In this figure, we can be see the mean value of the ratio between normalised transfer time and maximum He ppm. It can be observed that this ratio (it will name as Reaction) increase in the centre of furnace and its smaller in the wall.

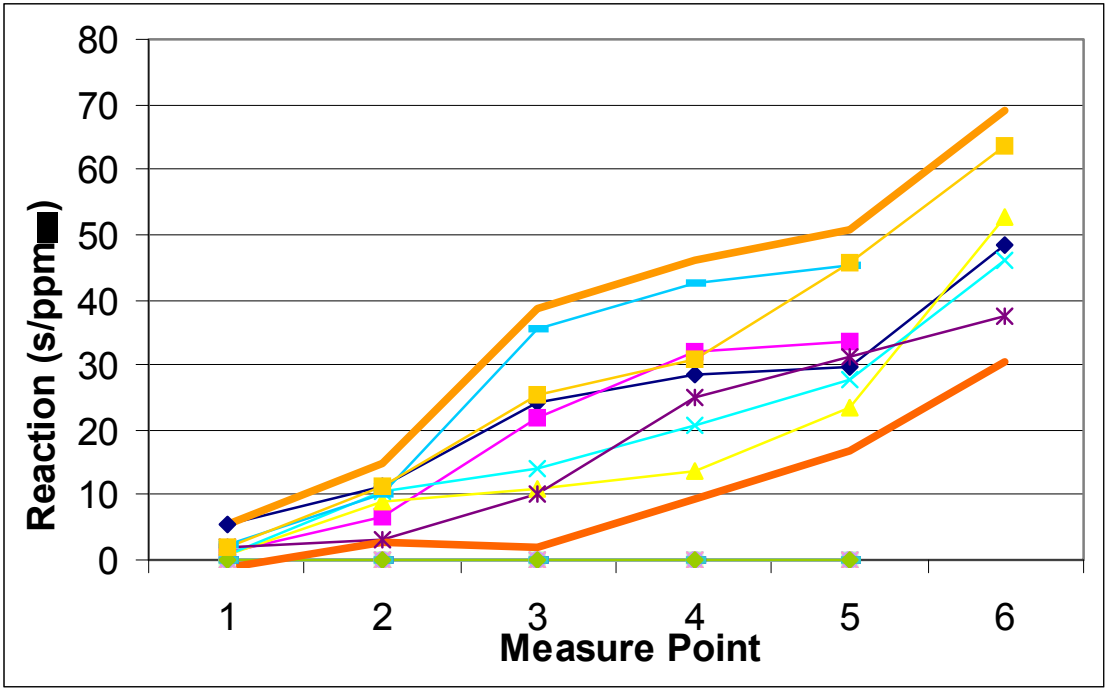


Fig. 5. In this figure has been represented the Reaction value obtained in all measures which technicians evaluated like “normal state” of furnace. In the figure have been included two gross lines that represent the mean value of Reaction plus/less the double of standard deviation for each point.

Additionally to normal data two calculated lines are drawing using the mean value plus/less the double of standard deviation for each point. These two lines will be considered as operation limits for a normal furnace state (see Fig. 5).
To represent all information in an optimum exposition, a ternary diagram representing the normalised variable named "Reaction" has been used. The six points of furnace define three specific working areas in the transversal section of the shaft: wall, medium and central. The wall area corresponds with the two first point's measure, the central area corresponds with the two last points and the two intermediate points correspond with medium area. Reactions profiles recorded during normal periods are shown in Fig. 6. The ranges of reaction in which furnace is correctly running are W (0-25%), M (40%-60%) and C (25%-50%).

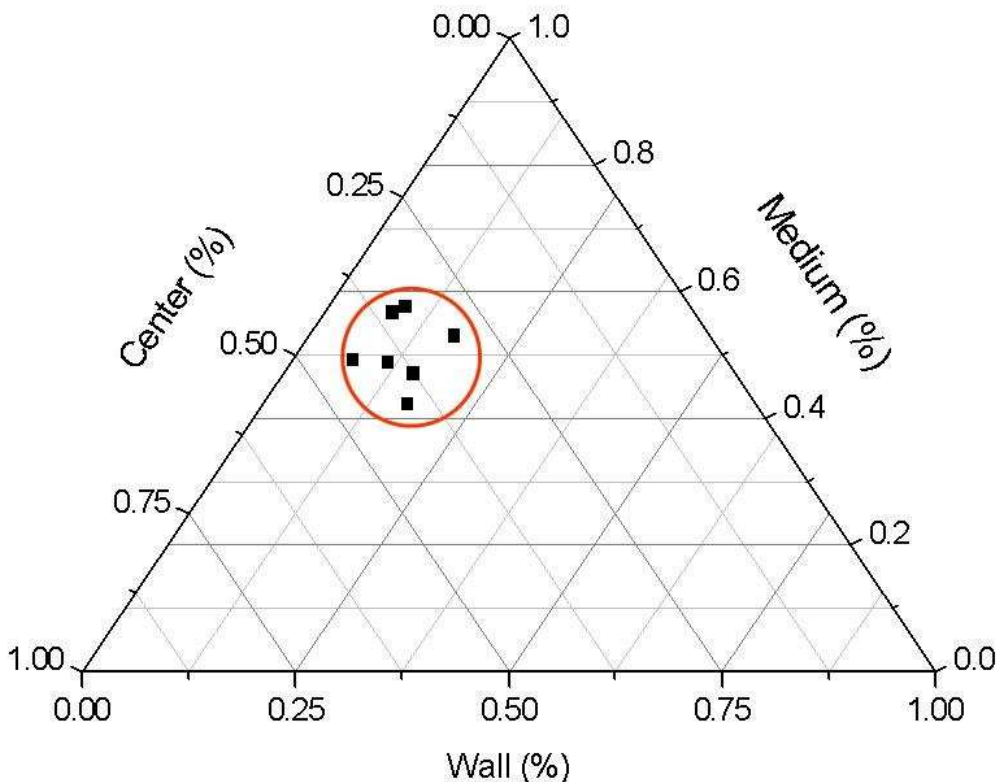


Fig. 6. In this figure it has been represented in a ternary diagram all measures evaluated by technicians as normal conditions. It can observed that all measures area grouped

It can be see that all points selected as "normal running" are grouped in the same area of the diagram. The points out this region represent 'non optimun' states of furnace, i.e, if the point is displaced at right then there are more reaction in the wall than in the centre and the furnace cooler can be observed.
The Fig. 7. represents all measures where the evaluation was certificated as "abnormal state". The points representing the measures are dispersed out of the area defined previously, except in two cases. It can be observed that almost always where the technicians indicated that the furnace was in abnormal state the measure realised by helium trazing

technique and evaluated with the variable Reaction showed an abnormal situation in the ternary diagram.

With this results, it is possible obtain only one parameter to characterise the evolution of blast furnace.

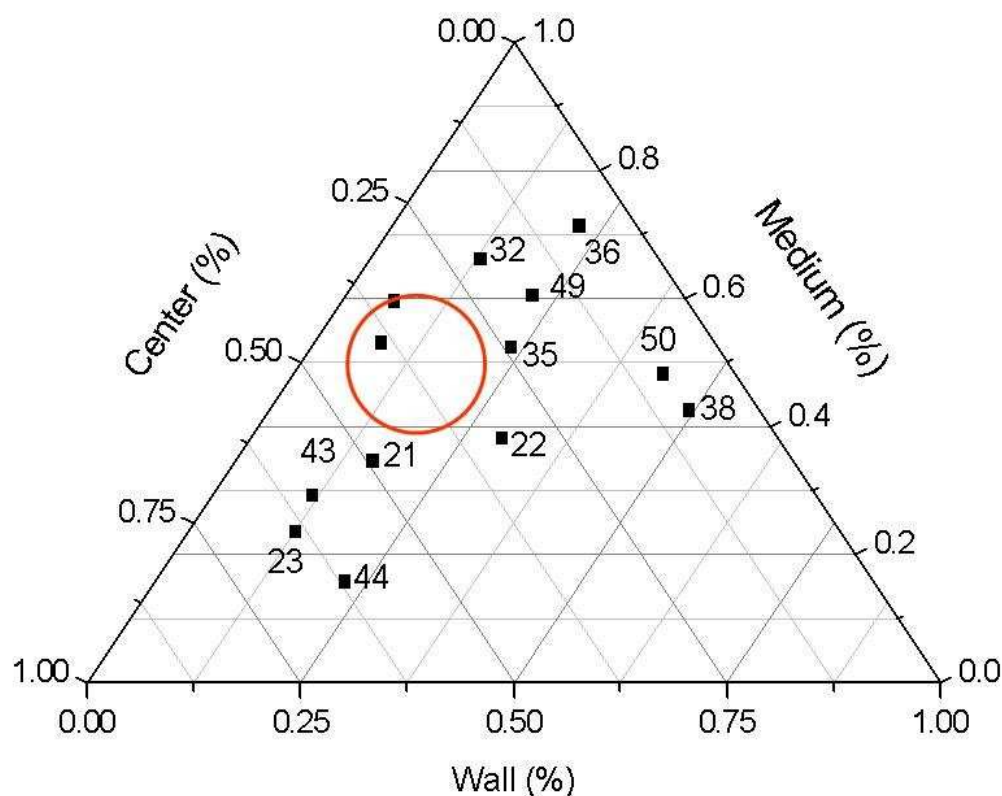


Fig. 7. In the figure it has been represented in a ternary diagram all measures evaluated by technicians as “abnormal state”. It can observe that these measures are dispersed by the ternary. The origin of an abnormal state in each measure can be different

4. Conclusions

Calculated variables from the measurements allow a concise characterization of the blast furnace state. Gas transfer measurements can be considered as a new tool to evaluate the state of a furnace in a specific moment because although the results do not have an excessive repeatability they can be a help to the operator.

The main advantage will be that employed only one measure it will be possible to evaluate the furnace.

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University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
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Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
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Phone: +86-21-62489820
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